SPIE's 6th Annual International Symposium on NDE of Aging Aircraft, Airports, and Aerospace Hardware (nd02), Newport Beach, CA 3-5 March 1999 -- paper 3586-35

Composite materials stiffness determination and defects characterization using enhanced leaky Lamb wave dispersion data acquisition method

Yoseph Bar-Cohen[a], Ajit K. Mal[b], Shyh-Shiuh Lih[a] and Zensheu Chang[a]

[a] Jet Propulsion Laboratory, Caltech, MS 82-105, 4800 Oak Grove Dr., Pasadena, CA 91109-8099, 818-394-2610, fax 818-393-4057, yosi@jpl.nasa.gov

[b] Mechanical and Aerospace Engineering Department, University of California, Los Angeles, CA 90095, ajit@seas.ucla.edu

ABSTRACT

The leaky Lamb waves (LLW) technique is approaching a maturity level that is making it attractive quantitative NDE tool for composites and bonded joints. Since it was first observed in 1982, the phenomenon has been studied extensively, particularly in composite materials. The wave is induced by oblique insonification using a pitch-catch arrangement and the plate wave modes are detected by identifying minima in the reflected spectra to obtain the dispersion data. The wave behavior in multi-orientation laminates was well documented and corroborated experimentally with high accuracy. The sensitivity of the wave to the elastic constants of the material and to its boundary condition led to the capability to measure the elastic properties of bonded joints. Recently, the authors significantly enhanced the LLW method capability by increasing the speed of the data acquisition, the number of the modes that can be identified and the accuracy of the data inversion. In spite of the theoretical and experimental progress, methods that employ oblique insonification of composites are still not being applied as standard industrial NDE methods. The authors investigated the issues that are hampering the transition of the LLW from becoming a standard NDE method and identified 4 key issues. The authors' progress and these issues will be described in this manuscript.

Keywords: Leaky Lamb Waves (LLW), NDE, Composites, Stiffness Constants, Aging Aircraft

1.0 INTRODUCTION

The high stiffness to weight ratio, low electromagnetic reflectance and the ability to imbed sensors/actuators made fiber-reinforced composites an important construction material of primary aircraft structures. These materials consist of fibers and a polymer matrix that are stacked in layers and then cured. The multiple step production process and the non-homogeneity with brittle matrix are making composites susceptible to formation of many possible defects throughout their life stages. Table 1 lists defects that may appear in composite laminates and their effect on the structural performance. A limiting factor in wide spread use of composites is their high cost - composite parts are about an order of magnitude more expensive than metallic parts. The cost of inspection is about 30% of the total cost of acquiring and operating composite structure. This large portion of the total cost makes the need for effective inspection critical not only to the operation safety [Bar-Cohen, 1991] but also to the cost benefit of these materials.

Generally, NDE methods are used to determine the structural integrity and stiffness of composite structures. While information about the integrity and stiffness can be extracted directly from NDE measurements, strength and durability can not be measured by NDE methods because these are not physically measurable parameters. For many years, the multi-layered anisotropic nature of composites posed a challenge to the NDE research community. Pulse-echo and through-transmission are still the leading standard NDE methods of determining the quality of composites. However, these methods provide limited and mostly qualitative information about defects and material properties. The discoveries of the leaky Lamb wave (LLW) [Bar-Cohen & Chimenti,1984] and the Polar Backscattering [Bar-Cohen & Crane, 1982] phenomena in composites enabled effective quantitative NDE of composites. These obliquely insonified ultrasonic wave techniques were studied both experimentally and analytically by numerous investigators [e.g., Bar-Cohen & Mal, 1988, Dayal & Kinra, 1991, and Nayfeh & Chimenti, 1988]. These studies led to the development of effective quantitative NDE capabilities for the determination of the elastic properties, to an accurate characterization of defects and even the evaluation the quality of adhesively bonded joints [Bar-Cohen, Mal & Lih, 1989].

TABLE 1: Effect of defects in composite materials

Defect	Effect on the material performance
Delamination	Catastrophic failure due to loss of the interlaminar shear carrying capability. Typical acceptance criteria require the detection of delaminations that are 0.25-inch or larger.
Impact damage	The effect on the compression static strength • Easily visible damage can cause 80% loss • Barely visible damage can cause 65% loss
Ply gap	Degradation depends on staking order and location. For $[0,45,90,-45]_{2S}$ laminate: - 9% strength reduction due to gap(s) in 0 ply - 17% reduction due to gap(s) in 90 ply
Ply waviness	• Strength loss can be predicted by assuming loss of load-carrying capability. • For 0 ply waviness in $[0,45,90,-45]_{2S}$ laminate, static strength reduction is: - 10% for slight waviness - 25% for extreme waviness • Fatigue life is reduced at least by a factor of 10
Porosity	• Degrades matrix dominated properties • 1% porosity reduces strength by 5% and fatigue life by 50% • Increases equilibrium moisture level • Aggravates thermal-spike phenomena
Surface notches	• Static strength reduction of up to 50% • Local delamination at notch • Strength reduction is small for notch sizes that are expected in service
Thermal Over-exposure	Matrix cracking, delamination, fiber debonding and permanent reduction in glass transition temperature

2.0 LEAKY LAMB WAVE PHENOMENON

The leaky Lamb wave (LLW) phenomenon is induced when a pitch-catch ultrasonic setup insonifies a plate-like solid immersed in fluid [Bar-Cohen, Mal and Lih 1993]. The phenomenon is the result of a resonant excitation of plate waves that leak waves into the water and interfere with the specular reflection. The experimental procedure involves the measurement of the reflections and the extraction of the dispersive spectral characteristics of the layered material. Evaluation of the minima in the reflection spectra at different angles of incidence provides information about the various wave modes in the form of dispersion curve. Dispersion curves for composite materials were analytically modeled and were very well corroborated experimentally confirming the accuracy of the model.

The experimental acquisition of dispersion curves for composite materials requires accurate control of the angle of incidence/reception and the polar angle with the fibers. The need to perform these measurements rapidly and accurately was effectively addressed at JPL where a specially designed LLW scanner was developed. With the aid of a personal computer, this scanner controls the height, angle of incidence and polar angle of the pitch-catch setup. The LLW scanner controls the angle of incidence/reception simultaneously while maintaining a pivot point on the part surface. A view of the LLW scanner installed on a C-scan unit is shown in Figure 1. A computer code was written to control the incidence and polar angles, the height of the transducers from the sample surface, and the transmitted frequency. In the past, the data acquisition involved the use of sequentially transmitted tone-bursts at single frequencies over a selected frequency range (within the 20dB level of the transducer set). Reflected signals are acquired as a function of the polar and incidence angle and are saved in a file for analysis and comparison with the theoretical predictions. The minima in the acquired reflection spectra represent the LLW modes and are used to prepare the dispersion curves (phase velocity as a function of frequency). The incident angle is changed incrementally within the selected range and the reflection spectra are acquired. For graphite/epoxy laminates the modes are identified for each angle of incidence in the range of 12° to 50° allowing the use of free-plate theoretical calculations. At each given incidence angle, the minima are identified and are added to the accumulating dispersion curves, and are plotted simultaneously on the computer display. While the data acquisition is in progress, the acquired minima are identified on both the reflection spectra and the dispersion curve.

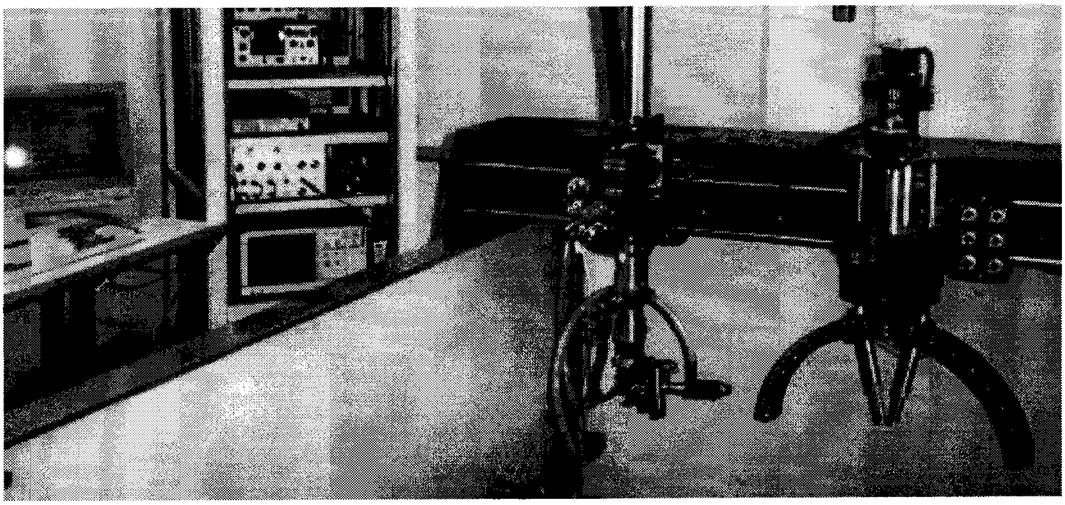

FIGURE 1: A view of the LLW scanner (on the right portion of the bridge) installed on the JPL's C-scan system

3.0 ISSUESAFFECTING THE PRACTICALITY OF LLW NDE

The issues that affect the transition of the LLW method to standard NDE application include:

1. Material density - The inverted material constants assume that the material density is known. NDE measurement of the material density can be done by radiographic tests. However, such tests are not economical and they require access from two sides of the test structure, therefore an alternative method of measuring the density is needed.
2. Multi-orientation laminates - The inversion algorithm developed for the determination of the elastic properties has been very successful for unidirectional laminates. The analysis of laminates with multi-orientation layers using ply-by-ply analysis is complex and leads to ill-posed results. The authors are currently studying methods of inverting the material elastic properties without the necessity to deal with the individual layers
3. Complex data acquisition - The LLW data acquisition setup is complex and the related process is not user friendly. The authors have significantly improved the data acquisition process, where a personal computer assists the user by optimizing the setup height to assure the greatest ratio between the maximum and minimum amplitudes in the reflected spectrum. The polar angle is set using the polar backscattering technique [Bar-Cohen and Crane, 1982] to determine the direction of the first layer. Further, a user friendly control software that operates on the Widows platform is being developed to allow interactive software control.
4. Time-consuming process - The formerly reported process of acquiring a dispersion curve was time consuming and took between 10 and 20 minutes for a single point. Recent development by the authors allows the measurement of the dispersion curves at a significantly higher speed. The experiment setup is depicted in Figure 2. At selected angles of incident the reflection spectral data is presented in real time directly on the digital scope after being amplified and rectified. A function generator induces a frequency sweep in the selected range and is fed to the X-axis of the digital scope whereas the amplitude of the received signals is fed to the Y-axis. A reference frequency marker is employed to calibrate the acquired spectral data when converting the received signal from the time domain to frequency domain. The reflection spectra are acquired in real time while filtering the high frequency noise and providing reliable data at a range of amplitudes that are significantly lower than were used in prior studies. Using this technique, a dispersion curve that is based on a set of 20 angles of incidence along a single polar angle is acquired in about 45 second. This method makes the process of acquiring LLW dispersion curves almost a real time one and is an important step towards making the method a practical quantitative tool for both inversion of the elastic properties and flaw characterization. An example of the computer display of the dispersion data and the inverted properties are shown in Figure 3.

   Using the new capability of rapid acquisition, various defects can be detected and characterized based on their dispersion curve data. In Figure 4a, the response from a defect-free graphite/epoxy laminate tested along the fibers is shown. In Figure 4b, the response from an area with a layer of simulated porosity (micro-balloons) is presented. As expected, at low frequencies the porosity has a relatively small effect and the dispersion curve appears similar to the one on Figure 4a. On the other hand, as the frequency increases, the response from the porosity layer behaves more like a delamination and it modifies the dispersion curve to appear the same as a laminate with half the thickness.

With regards to the inversion of the dispersion curves, it should be noted that the inversion equation is strongly nonlinear in c_{ij} (stiffness matrix) and H (thickness), and its solution is non-unique. Thus, extreme care must be taken in interpreting the numerical results obtained from the inversion of the dispersion data. Extensive parametric studies of inversion equation showed that only the thickness and the matrix dominated constants c_{22}, c_{23} and c_{55} can be determined accurately from the inversion of the dispersion data. The fiber dominated constants, c_{11} and c_{12}, can be determined from the travel times and amplitudes of reflected short-pulse signals in an oblique insonification experiment [Bar-Cohen, Mal and Lih 1993].

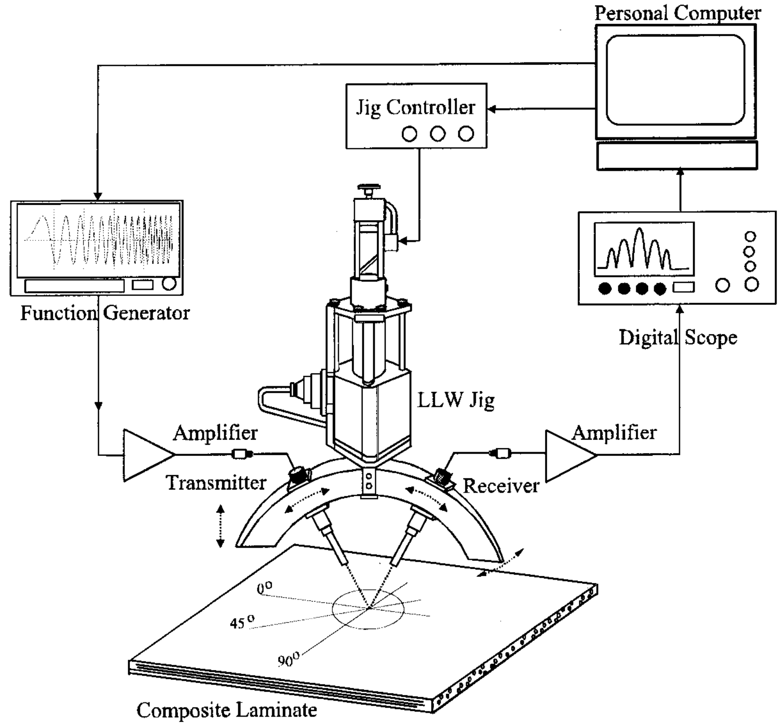

FIGURE 2: A schematic view of the rapid LLW test system.

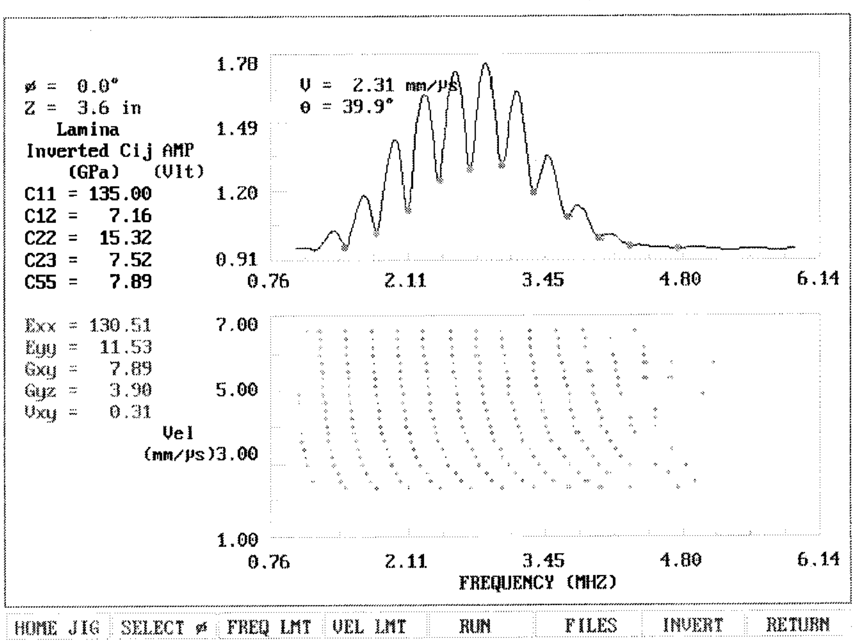

FIGURE 3: The computer display after the completion of the processes of data acquisition and inversion. The elastic stiffness constants are inverted from the dispersion curve and the results are presented on the left of the screen.

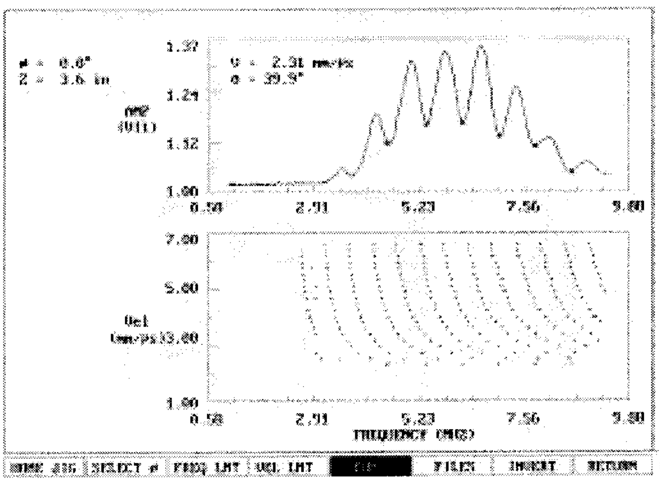

FIGURE 4a: The refection at 39.5 degrees incidence angle and the dispersion curve for a Gr/Ep $[0]_{24}$ laminate with no defects

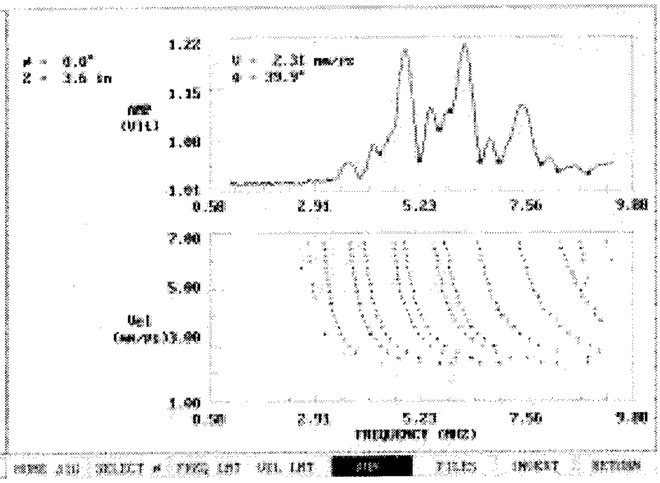

FIGURE 4b: The response at a defect area where porosity at the middle layer was simulated using microballoons.

4.0 RAPID IDENTIFICATION OF LLW MODES.

To enhance the accuracy of the inversion of the material stiffness constants, a method was developed to acquire dispersion curves and display them in a graphics format as shown in Figure 5. This method allows viewing modes at amplitude levels that are significantly smaller than observed ever before. The bright curved lines are showing the modes on the background of the reflected spectra. Methods of extracting the modes were investigated using image processing operators and neural network procedures. Once the curve of a specific mode is determined it is transformed to actual frequency vs. velocity data and then inversion is applied. This process involves a trade-off between noise suppression and localization, where the edge detection operator is used to reduce noise but it adds uncertainty to the location of the modes. Our approach consisted of using a linear operator that employs a first derivative Gaussian filter. This filter numerically approximated standard finite-difference for the first partial derivatives in the x and y directions. This type of operator is not rotationally symmetric and it is sensitive to the edge in the direction of steepest change, but acts as a smoothing operator in the direction along the edge.

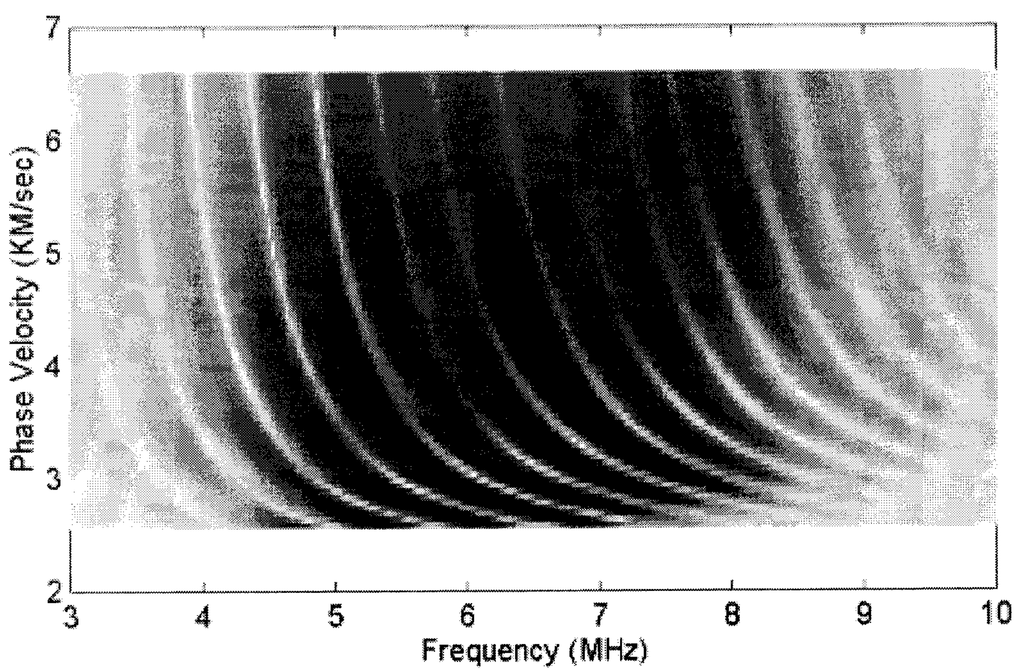

FIGURE 5: A graphic presentation of the dispersion curve from a unidirectional graphite/epoxy laminate.

5.0 CONCLUSIONS

The leaky Lamb wave (LLW) method has been studied by numerous investigators who contributed tremendously to the understanding of wave behavior in anisotropic materials. However, in spite of the progress the LLW method is still far from being an acceptable standard NDE method. The authors investigated the potential issues that are hampering this transition to practical NDE and identified 4 key issues: a) There is a need to determine the density nondestructively using access from a single-side; b) The analytical treatment of multilayered composites needs to assume global properties rather than using layer-by-layer analysis; c) The data acquisition process needs to be more user friendly; and d) The process of data acquisition needs to be rapid. The authors made significant progress in the simplification of the data process and the acquisition speed with some limited success being made on the modeling of composites as a global laminate. The inability to measure the material density with an NDE tool using access from a single side of a laminate is still considered an unresolved issue and will require further research efforts.

ACKNOWLEDGMENT

The Jet Propulsion Laboratory (JPL) portion of the research was carried out under a contract with National Aeronautics Space Agency (NASA). The UCLA research was supported by the AFOSR under grant F49620-93-1-0320 monitored by Dr. Walter Jones.

RERFERENCES

Bar-Cohen, Y., and R. L. Crane, "Acoustic-Backscattering Imaging of Subcritical Flaws in Composites," Materials Evaluation, Vol. 40, No. 9 (1982), pp. 970-975.

Bar-Cohen, Y., and D.E. Chimenti, Review of Progress in Quantitative NDE, Vol. 3B, D. O. Thompson & D.E. Chimenti (Eds.), Plenum Press, New York and London (1984), pp. 1043-1049.

Bar-Cohen, Y., and A. K. Mal, "Ultrasonic Inspection," Revised Chapter, Vol. 17, 9th Edition, Metals Handbook, NDE and Quality Control, ASM International, Metals Park, OH, 1989, pp. 231-277.

Bar-Cohen, Y., A. Mal, and S.-S. Lih, "NDE of Composite Materials Using Ultrasonic Oblique Insonification, Materials Evaluation, Vol. 51, No. 11, (1993), pp.1285-1295.

Dayal, V., and V.K. Kinra, J. Acoustic Society of America, Vol. 89, No. 4 (1991), pp. 1590-1598.

Mal, A. K., and Y. Bar-Cohen, Proceedings of the Joint ASME and SE meeting, AMD-Vol. 90, A. K. Mal and T.C.T. Ting (Eds.), ASME, NY, (1988), pp. 1-16.

Mal, A. K., C. -C. Yin, and Y. Bar-Cohen, "Ultrasonic NDE of Cracked Composite Laminates," Composites Engineering, Pergamon Press, Vol. 1, No. 2, (1991), pp. 85-101.

Nayfeh, A. H., and D. E. Chimenti, J. Applied Mechanics, Vol. 55 (1988) p. 863.